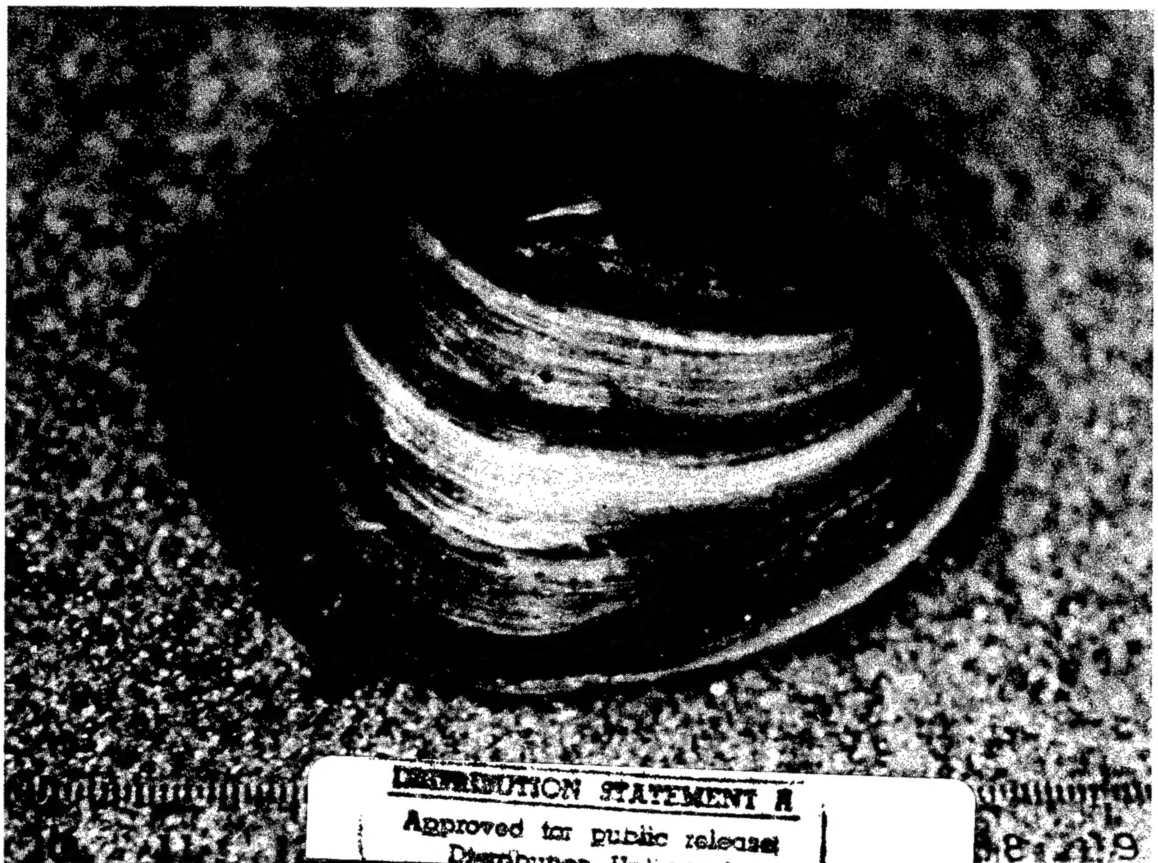
Effects of Contaminants on Naiad Mollusks (Unionidae): A Review



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Cover photo: *Lampsilis higginsi* is an endangered mussel found occasionally on the Upper Mississippi River System. The largest known population is at Prairie du Chien, Wisconsin, where this live female was collected. The scale at bottom of photo is in millimeters. *Photo by L. L. Marking.*

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Abstract

Although the uptake, storage, and elimination of contaminants by naiad mollusks has been studied, relatively little information is available on toxicity. Contaminants appear to have destroyed some populations directly by exerting toxic effects, or indirectly by causing or contributing to the elimination of essential food organisms or host fish. The most frequently studied contaminants are Cd, Cu, Mn-Mn^{54}, Pb-Pb^{210}, and Zn-Zn^{65}. Manganese seems to be most readily taken up and stored in tissues; no apparent damage has been reported from tissue concentrations of thousands of parts per million (ppm) and the element appears to be essential to metabolism. Zinc and cadmium also accumulate at high levels in tissues. Lead was never found to be lethal in the studies reviewed. Various common contaminants have been reported to be toxic at the following concentrations (ppm): cadmium, 2; copper sulfate, 2 to 18.7; ammonia, 5; potassium, 11; chromium, 12.4; arsenic trioxide, 16; copper, 19; and zinc, 66. In long-term exposures, concentrations of copper as low as 25 parts per billion (ppb) were lethal. Fry of fish infected with 20–35 glochidia were more sensitive than uninfected fish to toluene, naphthalene, and crude oil. Although few specific adverse impacts of contaminants have become clearly evident, circumstantial evidence leaves little doubt that contaminants have been responsible for decreases in population density, range, and diversity. Stresses that have been responsible for the disappearance of naiad mollusks in contaminated areas have not generally been identified, and the components of the stresses have seldom been quantitatively and qualitatively correlated with the composition and size of the naiad fauna. Often two or more factors appear to work in combination to produce

the total stress that adversely affects populations. Naiad mollusks are important indicators of contaminants in the environment; residues in soft tissue indicate recent or current exposure, and residues in shells indicate past exposure.

The chemical composition of the medium in which an animal lives is reflected in the chemical composition of the organism. In a literature summary, Vinogradov (1953) reported that investigators were identifying natural components of mollusk shells as early as 1814 and of soft parts by 1905.

Higgins (1858), who reported decreasing species of Unionidae (naiad mollusks) in Ohio streams, attributed the dwindling numbers to the pioneer activity of bringing wilderness land under cultivation. Lewis (1868) reported that a serious decline of *Anodonta lewisii* in the Erie Canal, New York, was caused by chemical contamination, and Bradley (1907*a*) was among the first to identify trace elements in unionids. Contaminants have thus been known in naiades for as long as man has been able to identify them.

Thriving populations are typically associated with high dissolved oxygen concentrations and other physicochemical conditions that are characteristic of unpolluted water (Ingram 1956). Oxygen concentrations of 2.5 to 5.0 ppm or higher are required to support survival and growth as measured at the bottom-water interface where naiades live (Ellis 1931*a*,*b*; Imlay 1971; Horne and McIntosh 1979).

Declines in naiad populations have been attributed by 20th century researchers to a variety of factors, including waterway modifications, streambed changes, commercial mussel fishing, water quality deterioration, sedimentation, agricultural runoff, industrial pollution, commercial barge activities, and competition from the exotic Asiatic clam *Corbicula* sp. (Ortmann 1909; Baker 1922; Ellis 1931*b*, 1936; van der Schalie 1938; Athearn 1967; Isom 1969; Stansbery 1970; Dineen 1971; Fuller 1974, 1978, 1980*a*,*b*; Strayer 1980; Gordon 1982). Little quantitative information is available on the precise effects of the individual factors, but evidence is overwhelming that the resultant stresses, individual or combined, were responsible for the deterioration of the naiad fauna in many streams. This deterioration has been especially noticeable in the Mississippi River and its tributaries.

Analyses of the early surveys by Ellis (1931*a*, *b*), summarized by van der Schalie and van der Schalie (1950), indicated that 39 species occurred in the Upper Mississippi River in 1930. A continuing trend toward diminishing species diversity and density was shown in surveys by Havlik and Stansbery (1977), Fuller (1978, 1980*b*), Ecological Analysts, Inc. (1981), Thiel (1981), Duncan and Thiel (1983), and Havlik (1983). Populations, range, and habitats of *Lampsilis higginsi* have dwindled in the Upper Mississippi River to the extent that the species has been placed on Federal and State lists of endangered species. And *Potamilus capax*—another endangered species—has not been found alive in the Upper Mississippi River System since the 1930's.

Fuller (1980*a*) wrote that 70% of the original 50 taxa no longer thrived in the Upper Mississippi River. In a survey of naiad communities of the Upper Mississippi River System, he identified zones where populations were categorized as "unhealthy" because density, diversity, and recruitment were low. One of these zones, near Twin Cities (Minneapolis–St. Paul), Minnesota, extended from St. Anthony Falls through Lake Pepin (142 km). Another zone was the 265-km section of the Mississippi River below the mouth of the Des Moines River, Iowa. The 645-km section between these two areas—especially the 181-km length of Pools 6–10, and Pool 17—was regarded as a recovery zone; however, even in this section not all species were thriving.

The Illinois River, a large tributary of the Mississippi, was one of the more productive naiad streams in the United States in the early 1900's; by the 1970's, however, less than half of the original species remained (Starrett 1971; Anderson et al. 1978). The Minnesota River, another tributary of the Mississippi, was classified as relatively unpolluted by Wiebe (1927), and Dawley (1947) reported that it once supported a flourishing naiad community of 32 species. By the mid-1970's, how-

ever, agricultural runoff had eradicated naiades in the lower 24 km of this river (Fuller 1978).

Naiades are reliable indicators of pollution; being sedentary and occupying a low position on the food chain, they are rapidly affected when water quality deteriorates (Ortmann 1909; Stansbery and Stein 1971; Fuller 1974; Horne and McIntosh 1979; Forester 1980). Fuller (1974) wrote that they have extraordinary value as qualitative indicators of the presence of pesticides, radionuclides, and trace elements found in nature or in waste materials. In fact, McCleneghan et al. (1981) reported that the species *Anodonta californiensis* and *Gonidea angulata* were used in monitoring toxic substances at several sites in California. Brief accounts of the effects of certain contaminants on naiades were reported by Ingram (1956), Fuller (1974), Imlay (1971, 1980, 1982), and Kidder (1977), but a comprehensive compilation and evaluation of contaminants in soft parts and shell material has not been published.

Trace metals and incidental elements are here treated as contaminants. Although manganese, for example, is generally considered an essential element and not a contaminant, we include it because the concentrations identified were often extremely high. Also, radioactive Mn that has been introduced into the environment can be considered as a contaminant.

The objectives of this study were to (1) identify the effects of contaminants on naiad mollusks from reports in the literature; (2) summarize and evaluate the literature and identify the levels of contaminants that are detrimental to them; and (3) identify data gaps and research needs.

We briefly describe our literature review techniques and offer an overview of the effects of metals and contaminants on naiad mollusks. A tabular summary (Table 1) follows, with brief annotations on more than 80 references. The relation of unionids to contaminants is then briefly discussed on the basis of the literature reviewed.

Review Techniques

We compiled this review from a computer search based on Dialog Information Services, and the indexes of *Nautilus, Bulletin of the American Malacological Union, American Midland Naturalist, Sterkiana,* and *Titles and Abstracts of North American Benthological Society.* In addition, numerous references came from literature cited by authors of articles that we examined.

Information was summarized and evaluated, and contaminants were categorized into groups of closely associated elements or materials such as metals (including radionuclides), pesticides, and miscellaneous contaminants not related to the other two groups. The sequence of metals is alphabetized; units of measurements are those used in the original references.

Results

Metals and Radionuclides

Metals most frequently studied were Zn-Zn^{65} (23), Mn-Mn^{54} (20), Cu (16), Cd (15), and Pb-Pb^{210} (14). Zinc was reported toxic to naiades in only 1 of 23 studies; the LC50 was 66 mg/L in 336-h exposures. Cadmium was the most toxic of the metals; toxicity was reported at 2 mg/L. The toxicity of $CuSO_4$ ranged from 2 to 18.7 mg/L in acute exposures and was as low as 25 ppb in long-term exposures. Other toxic contaminants were As_2O_3 at 16 ppm in acute exposures, and potassium at 11 ppm in 36 to 52 days or 7 ppm in 8 months. Manganese and lead are not known to produce toxicity.

Manganese is readily accumulated and stored in tissues, particularly the gills, of naiad mollusks. The highest concentration factor reported for Mn was 40,000 in soft parts and 14,000 in shells, even where the concentration in water was undetectable (Gaglione and Ravera 1964). In soft-water lakes of the Canadian Shield in Ontario, *Anodonta grandis* concentrated 3,500 ppm of Mn in soft parts (Forester 1980). In the Columbia River, concentrations of Mn in *A. wahlamatensis* were 18,699 ppm in the gills, 5,092 ppm in the mantle, 1,164 ppm in the visceral sac, and 212 ppm in the muscle (Johnson et al. 1966). Naiades were found only in lakes where manganiferous material was present, strongly indicating that manganese is an essential element; indeed, Mn has long been considered to be important in metabolism (Bradley 1910). None of the authors reported reasons for the high levels of Mn found in tissues. Grasse (1960)

Table 1. *Principal effects of contaminants on naiad mollusks: review of the literature, 1907-1984 (contaminant, locality, reference, and effects).*

In the first section, references to metals and radionuclides are keyed alphabetically to entries. 1-42 as follows: Ag 1,2; Al 3; As 4,5,6,7; Ba 1,8; Ba^{140}-La^{140} 9; Ca 10; Ce^{141} 9; Ce^{144} 9,19,20,21; Cd 1,3,5,6,7,8,11,12,13,14,15,16, 17,18; Co 11,22; Co^{60} 19,23,24,25; Cr 5,11,22,26; Cr^{51} 19,23; Cs^{137} 9,19,20,24; Cu 1,3,5,8,11,12,13,14,22,27,28, 29,30,31; Eu^{155} 23; Fe 1,8,12,15,29,30; Fe^{59} 23; Hg 1,2,5,6,12,13,16,32; Hg^{203} 23; I^{131} 33;K 34; Li 11,29; Mg 1; Mn 1,3,8,12,15,29,30,35; Mn^{54} 9,19,21,23,25,36; Na 1; Ni 1,3,5,11,13,29; P^{32} 20; Pb 1,3,5,6,7,8,11,12,13,14,17, 22, 31; Pb^{210} 23; Ra^{226} 21; Ru^{103} 20; Ru^{106} 9,21; Ru^{163} 9; S^{35} 19; Sc^{46} 23; Se 5; Sn 5; Sr 1,10,29,39; Sr^{85} 24,37; Sr^{89} 20; Sr^{90} 10,19,38,39; Ta^{182} 23; Tc^{99} 40; Zn 1,3,5,7,8,11,12,13,14,15,16,18,22,30,41; Zn^{65} 9,19,23,24,25,36,42; and Zr^{95}-Nb^{95} 9,20.

Metals and Radionuclides

1 Ag, Ba, Cd, Cu, Fe, Hg, Mg, Mn, Na, Ni, Pb, Sr, Zn
Various rivers in United States (Imlay 1982)
Growth rate decreased in freshwater mussels exposed to pollution and stress. Disturbance rings in shells were useful for monitoring metal contamination. The rings differed with species, age, and layer, but not with sex. Numerous concentration factors for metals were reported.

2 Ag, Hg
Laboratory, Rochester, New York (Terhaar et al. 1977)
Ligumia sp. and *Margaritifera* sp. exposed to Hg and Ag for 10 weeks accumulated the metals with no consistent pattern. Concentration indices and variation were greater for Hg than for Ag. Freshwater mussels were regarded as poor indicators of Hg contamination.

3 Al, Cd, Cu, Mn, Ni, Pb, Zn
Lakes in south-central Ontario, Canada (Forester 1980)
Anodonta grandis from 15 south-central Ontario lakes concentrated high levels of metals in soft parts. Concentrations (ppm) were highest for 7 of the 17 elements studied: Mn, 3,500; Al, 1,500; Zn, 200; Pb, 18; Cd,17; Cu, 6; and Ni, 1.2.

4 As
Laboratory, University of Missouri, Missouri (Ellis 1937)
Amblema peruviana exposed to $As_2 0_3$ in hard water survived at a concentration of 8 ppm, but died within 3-16 days at 16 ppm.

5 As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Sn, Zn
Lake George, New York (Heit et al. 1980)
Lampsilis radiata, *Elliptio complanatus*, and *Anodonta grandis* concentrated Cd, Cu, Hg, Se, and Zn above levels found in sediment. Concentrations in tissues were similar to those in sediments for Cr, Ni, and Pb, but lower than those in sediments for As and Sn.

6 As, Cd, Hg, Pb
Lake Washington and Sardis Reservoir, Mississippi (Price and Knight 1978)
Arsenic levels were consistently low in all clam species. Concentrations of Cd were uniform among eight species. The smaller individuals contained the higher concentrations of Hg. Ranges of mean concentration (ppm) for eight species were as follows: As, 0.06-0.36; Cd, 0.086-0.311; Hg, 0.001-0.087; and Pb, 0.330-9.433.

7 As, Cd, Pb, Zn
Cedar Creek, Gasconade, Big, and Bourbeuse rivers, Missouri (Gardner et al. 1981)
Concentrations of free amino acids, which were related to stress, were elevated in the tissues of *Amblema plicata* sampled from streams contaminated with acid mine drainage. In mussels from Big River, Pb and Cd concentrations were higher in soft tissues—160 and 5.9 $\mu g/g$, respectively—than in shells.

8 Ba, Cd, Cu, Fe, Mn, Pb, Zn
Big and Black rivers, Missouri (Schmitt and Finger 1982)
Concentrations of metals were elevated in pocketbook mussels (*Lampsilis ventricosa*) collected at sites contaminated with Pb tailings. At the Brown's Ford site, concentrations in soft tissue ($\mu g/g$, dry weight) were Ba, 193; Cd, 33; Cu, 61; Fe, 1,653; Mn, 11,367; Pb, 387; and Zn, 5,967. In shell material, the values were Ba, 335; Cd, 0.7; Cu, 2.5; Fe, 89; Mn, 385; Pb, 19; and Zn, 36.

9 Ba^{140}-La^{140}, Ce^{141}, Ce^{144}, Cs^{137}, Mn^{54}, Ru^{106}, Ru^{163}, Zn^{65}, Zr^{95}-Nb^{95}
Lower Trent and Neuse rivers, North Carolina (Wolfe and Schelske 1969)
Among radioisotopes, only Mn^{54} and Ru^{106} were detected in *Elliptio complanatus* collected every 4-6 weeks for 1 year after two 1966 nuclear tests. Movement of fallout activity through the aquatic environment was very rapid.

Table 1. *Continued.*

10 Ca, Sr, Sr^{90}

Clinch and Tennessee rivers (Nelson 1963)

Calcium content in 16 species of clams was fairly constant at 40% of shell ash weight. Sr content ranged from 156 $\mu g/g$ for *Quadrula quadrula* to 382 $\mu g/g$ for *Anodonta corpulenta*; differences in Sr content were due to inherent species variation, rather than to ratios of Sr to Ca in the environment. Sr content seemed to increase with growth rate and with reduced surface-to-volume ratio.

11 Cd, Co, Cr, Cu, Li, Ni, Pb, Zn

Illinois River, Illinois (Mathis and Cummings 1973)

Metal concentrations in bottom-dwelling organisms were closely correlated with concentrations in bottom sediments. Concentrations of most metals were highest in worms (one exception: Zn was highest in mussels), intermediate in mussels (*Fusconaia flava*, *Amblema plicata*, and *Quadrula quadrula*), and lowest in fish. Accumulations of metals were highest in sediments, intermediate in organisms, and lowest in water.

12 Cd, Cu, Fe, Hg, Mn, Pb, Zn

Lake Balaton, Hungary (Salanki et al. 1982)

Metal concentrations varied with species and tissue. Most Cd was found in gills of *Unio pictorum* and most Mn, Pb, and Zn in gills of *Anodonta cygnea*. Concentration factors applicable to *A. cygnea* gills were 350,000 for Mn; 28,000 for Fe; 24,000 for Pb; 8,100 for Zn; 4,600 for Cd; 2,300 for Cu; and 1,600 for Hg.

13 Cd, Cu, Hg, Ni, Pb, Zn

River Thames, England (Manly and George 1977)

Anodonta anatina accumulated substantial quantities of Zn, Ni, Pb, and Cd. Concentrations in soft tissue were correlated with those in the environment, although waterborne concentrations varied substantially. Concentrations were highest in tissues of the mantle, ctenidia, and kidney. Concentrations were highly variable in animals from the same locality, especially among immature specimens.

14 Cd, Cu, Pb, Zn

Fox River, Wisconsin and Illinois (Anderson 1977)

Concentrations of metals in bodies of freshwater mussels correlated with those in the sediments, which were higher than those in water, whereas concentrations in shells correlated with those in water. Zn was an exception and was concentrated primarily in the body; concentrations in *Lasmigona complanata* ($\mu g/g$) were as follows: gill, 421; viscera, 271; muscle, 62; and shell, 5. Five other species of freshwater mussels responded similarly.

15 Cd, Fe, Mn, Zn

River Murray, South Australia (Jones and Walker 1979)

Metal loads in *Velesunio ambiguus* varied markedly between individuals from the same population, due partly to systematic relations between metal loads, body weight, and age (but not sex). This mussel may be suitable for long-term monitoring and for comparison of metal concentration between sites, after the variability is taken into account.

16 Cd, Hg, Zn

Willamette River, Oregon (Mellinger 1972; Mellinger and Willis 1973)

Uptake of these metals in *Margaritifera margaritifera* continued for 39 to 80 days before near-equilibrium concentrations were reached. Distribution in tissues was constant. Retention after 81 days in uncontaminated water was 76% for $CdCl_2$, 87% for CH_3HgCl_2, 69% for $HgNO_3$, and 57% for $ZnCl_2$. Specimens exposed to 2.0 ppm Cd died within 88 h and those exposed to 4.0 ppm died within 61 h.

17 Cd, Pb

Big River, Missouri (Czarnezki 1983)

When pocketbook mussels (*Lampsilis ventricosa*) were caged above and below tailing deposits from an abandoned mine, those in downstream cages accumulated significantly higher concentrations of Cd and Pb. Mussels were considered useful monitors because they accumulated these contaminants at higher and faster rates than did other organisms.

18 Cd, Zn

Williamson Ditch and Trimble Creek, Indiana (Adams et al. 1981)

Specimens of *Amblema perplicata* from uncontaminated water were placed in contaminated streams for 1 week. Concentrations of Zn were highest in gill tissue (956 $\mu g/g$) and those of Cd were highest in digestive glands (186 $\mu g/g$). The values were significantly higher than those in background and control clams. Particular organs of clams may be useful for monitoring Zn and Cd in freshwater systems.

Table 1. *Continued.*

19 Ce^{144}, Co^{60}, Cr^{51}, Cs^{137}, Mn^{54}, S^{35}, Sr^{90}, Zn^{65}
Savannah River, South Carolina (Harvey 1969)
Specimens of *Lampsilis radiata* exposed to low concentrations of radionuclides in a reactor effluent stream for 91 days were transferred to a nonradioactive stream to determine retention. Only Cs^{137}, Mn^{54}, and Sr^{90} were concentrated significantly in shells. All nuclides except Sr^{90} accumulated in soft tissues, in which concentration factors were as follows: Zn^{65}, 4,100; Mn^{54}, 2,400; Ce^{144}, 900; Co^{60}, 790; Cr^{51}, 440; S^{35}, 240; and Cs^{137}, 220. Concentration factors in shells were Sr^{90}, 1,330; Mn^{54}, 1,150; and Cs^{137}, 25.

20 Ce^{144}, Cs^{137}, P^{32}, Ru^{103}, Sr^{89}, Zr^{95}-Nb^{95}
Laboratory, Norway (Garder and Skulberg 1965)
Specimens of *Anodonta piscinalis* exposed for 125 days to radionuclides reached equilibrium concentrations after 30 days of exposure. Accumulation in order of decreasing affinity was $P^{32} > Sr^{89} > Ce^{144} > Ru^{103} > Cs^{137} > Zr^{95}$-$Nb^{95}$. This species shows promise for monitoring of these radionuclides.

21 Ce^{144}, Mn^{54}, Ra^{226}, Ru^{106}
Lake Maggiore, Italy (Gaglione and Ravera 1964, Ravera 1964)
Mn^{54} was present in high quantities in soft parts and shells of *Unio mancus* var. *elongatulus*, even though it was undetectable in water, sediment, or other organisms. The concentration of Mn^{54} was 3 times higher in this species than in *Anodonta cygnea*. Concentration factors were 11,000 to 40,000 for soft tissues and about 14,000 for shells. Tissue preference was gill > mantle > visceral sac. Concentration rates of Mn^{54} differed significantly among tissues but were uniform in shells. Concentrations of Mn^{54} in mollusks appeared to be a valid index of Mn^{54} contamination of the environment.

22 Co, Cr, Cu, Pb, Zn
Kingston Basin, Canada (Lord et al. 1975)
Soft tissues of *Lampsilis radiata* contained the following concentrations (ppm, dry weight): Zn, 225; Cu, 36; Cr, 19; Pb, 4.7; and Co, 1.1. These levels were attained by accumulation of uptake from water and from ingested particulate material. The use of freshwater mussels for monitoring specific chemicals in aquatic environments was recommended.

23 Co^{60}, Cr^{51}, Eu^{155}, Fe^{59}, Hg^{203}, Mn^{54}, Pb^{210}, Sc^{46}, Ta^{182}, Zn^{65}
Laboratory, California (Harrison and Quinn 1972)
Anodonta nuttalliana was exposed to low water concentrations of radionuclides for 10–12 days. Concentrations of Mn^{54}, Co^{60}, Pb^{210}, and Zn^{65} were high in calcareous tissue, and those of other nuclides were high in digestive organs. The valence of nuclides affected distribution patterns: divalent ions were in calcareous tissue and trivalent ions in digestive organs. In this extensive study, the order of accumulation in calcareous tissue was $Mn^{54} > Zn^{65} > Co^{60} > Pb^{210}$.

24 Co^{60}, Cs^{137}, Sr^{85}, Zn^{65}
Laboratory, Cincinnati, Ohio (Brungs 1967)
Radionuclides added to a small pond accumulated more rapidly in soft parts than in shells of *Lampsilis radiata siliquoidea*. Shells continued to accumulate nuclides, whereas soft parts gradually lost radioactivity as water concentrations decreased. Young clams accumulated more Zn^{65} and Sr^{85} than did adults.

25 Co^{60}, Mn^{54}, Zn^{65}
Columbia River, Oregon (Johnson et al. 1966)
Tissue distribution reflected biochemical specificity for metals. *Anodonta wahlamatensis* showed concentrations of $Zn^{65} > Mn^{54} > Co^{60}$. For Zn^{65}, wet weight and (in parentheses) dry weight values (pCi/g) were as follows: gill, 56.90 (2,845.1); mantle, 352.1 (1,247.7); viscera, 57.5 (285.4); and muscle (wet weight only), 23.6.

26 Cr
Laboratory, China (Chin and Chow 1978)
The 96-h LC50 for Cr^{+6} to *Hyriopsis cumingii* was 12.4 ppm at 19 °C and 8.8 ppm at 23 °C. Heavy metals were more toxic to mollusks than to fish.

27 Cu
Laboratory, Duluth, Minnesota (Imlay 1971)
In long-term exposures of several months, Cu was lethal to freshwater mussels at 25 ppb. Mussels were about as sensitive as other invertebrates and fish; exposure to lower levels of Cu may have affected growth and reproduction.

Table 1. *Continued.*

Muskingum River, McConnelsville, Ohio (Bates and Dennis 1976)
Effluents discharged into the Muskingum River often exceeded 45 kg of Cu per day. A body burden of about 20 mg/kg (wet tissue weight) was lethal to mussels. Lethal concentrations extended for about 48 km below the point of discharge. An estimated 17.5 million mussels were killed by the discharge.

Muskingum River, McConnelsville, Ohio (Foster and Bates 1978)
Cu accumulated in *Quadrula quadrula* caged below a point source. Mean tissue concentrations were 2.2 μg/g above the outfall, and below the outfall ranged from 18.7 μg/g at 5 km to 5.8 μg/g at 69 km. Mortality occurred after 11 days and adverse impacts were evident as far as 21 km below the outfall. Freshwater mussels were useful for evaluating the effects of point source pollution.

28 Cu complexes
Moscow River, Russia (Kapkov 1973)
Cu complexes were toxic at 2 mg/mL to *Unio tumidus*, *U. pictorum*, and *Andonta piscinalis* in 7.5 to 10.5 days of exposure. The effects induced by copper complexes were more toxic than those induced by ionic copper.

29 Cu, Fe, Li, Mn, Ni, Sr
Various natural waters, England (Fox and Ramage 1931)
Spectrographic analysis of *Anodonta cygnea* showed its gills to be "rich" in Mn. Cu, Fe, Li, Ni, and Sr were also found, but a number of other trace metals (Ag, Ba, Cd, Co, F, Pb, Rb) were not detected by the methods used.

30 Cu, Fe, Mn, Zn
Crisfield, Maryland (McHargue 1924, 1927)
A mixed sample of soft tissue of *Unio* sp. and *Anodonta* sp. contained the following concentrations (ppm): Mn, 5,424; Fe, 1,325; Zn, 750; and Cu, 12.3. Mn, Zn, and Cu were considered vital in shellfish metabolism.

31 Cu, Pb
Lake Balaton, Hungary (Salanki and Varanka 1976)
$CuSO_4$ was lethal to *Anodonta cygnea* at 10 mg/L in a 10-h exposure, and concentrations as low as 0.00001 mg/L reduced filtering activity. Neither $PbCl_2$ nor $Pb(NO_3)_2$ caused noticeable change in activity at 0.1 and 10 mg/L. This exposure method was useful for testing sublethal effects.

32 Hg
Kentucky Lake, Tennessee (Yokley 1972)
Concentrations of Hg increased from spring to fall in water and mussel tissues sampled for 1 year. Concentrations in tissues were highest during periods of high flow. Concentrations were as high as 0.55 μg/L in water and averaged from 1.0 to 2.5 μg/g in nine taxa of mussels.

Minnedosa Lake, Manitoba, and Clay Lake, Ontario, Canada (Smith et al. 1975)
Rate of Hg uptake increased with increasing water concentrations and varied among chemical forms: methylmercuric chloride > phenylmercuric acetate > mercuric chloride. Only methylmercuric chloride accumulated extensively in the foot muscle. *Anodonta grandis* accumulated less Hg than did *Lampsilis radiata* or *Lasmigona complanata*. Elimination of Hg was faster from the gill and liver than from other tissues during an 8-week period in uncontaminated water. Water must seemingly be heavily contaminated with Hg before concentrations in mussel tissues become elevated. Temperature did not affect uptake rate.

Paglia River, Italy (Renzoni and Bacci 1976)
Concentrations of Hg (μg/g) in *Unio* cfr. *elongatulus* were highest in digestive glands (1.4) and gills (1.3), and lowest in adductor muscle (0.8). The metal was rapidly eliminated after the mussels were transferred to clean water.

33 I^{131}
Fern Lake, Washington (Short et al. 1969)
Margaritifera margaritifera exposed to I^{131} accumulated measurable quantities in shell and soft parts within 10 h and continued the accumulation for 13 days. Accumulation factors were 47 for soft parts and 75 for shell.

34 K
Various rivers in United States (Imlay 1973)
Exposure to 11 ppm K was lethal to *Actinonaias carinata*, *Lampsilis radiata siliquoidea*, and *Fusconaia flava*

Table 1. *Continued.*

in 36 to 52 days, and exposure to 7 ppm was lethal in 8 months. Presence of mussels in river systems was correlated with K levels in water.

35 Mn

Lakes near Madison, Wisconsin (Bradley 1907*a,b*)

Mn was present in considerable quantities (0.93–1.19%) in tissues of *Unio* sp. and *Anodonta* sp., and was considered as possibly being a normal constituent of tissues.

Mississippi, St. Lawrence, and Atlantic drainage; Wisconsin lakes (Bradley 1910)

Mn was abundant in all specimens in all waters; tissue concentrations (%) were 2.46 in mantle, 2.11 in liver, 1.64 in gills, 0.29 in muscle, and 0.75 in eggs. Mussels were found only in lakes containing manganiferous bacteria such as *Crenothrix*. Mn was concentrated to a tissue level of 1.84% from water containing only 0.0000066%. Mn was considered important in metabolism.

Lake Maggiore, Italy (Merlini et al. 1965)

Accumulation of fallout Mn^{54} and stable Mn were correlated in freshwater mollusks. Soft tissue of *Anodonta cygnea* contained high concentrations (ppm) of Mn^{54}; gills, 18,699; mantle, 5,092; visceral sac, 1,164; and muscle, 212. In shells, Mn was nonhomogeneously distributed, and concentrations increased with size of the mussel. There was little difference in Mn content of mollusks collected from different sites.

Lake Ontario, Canada (Gabay et al. 1966)

Concentrations of Mn^{54} were higher in tissues than in shells of *Lampsilis* sp. Mn was not detectable in surface water.

Laboratory, Livermore, California (Harrison 1966)

Anodonta nuttalliana concentrated the metal when exposed to 0.1 ppm Mn^{54} in water, but lost 33% of the accumulated radioactivity after 10 days in nonradioactive water. Main site of Mn^{54} concentration was a calcareous tissue located near the gill attachment; concentrations were as high as 3% (dry weight). Other metals—Ca^{45}, Zn^{65}, and Co^{60}—also accumulated in this tissue.

Ottawa River, Canada (Seah and Hobden 1969)

Gill tissues of *Elliptio complanatus* contained 2.17 mg of Mn per gram of tissue (mantle, 0.47; other soft parts, 0.02–0.08). Mn^{54} was in a stable form in tissue. The Mn in gill tissues may represent an excretory form.

Muskingum River, Ohio (Pruiskma et al. 1981)

Shell concentrations of Mn in *Quadrula quadrula, Q. pustulosa, Amblema p. plicata, Obliquaria reflexa,* and *Obovaria subrotunda* ranged from 276 to 1,008 ppm. Different accumulation rates were related to differing environmental conditions. Authors regarded Mn as a contaminant from coal mine wastes and suggested that accumulation may be related to replacement of Ca in the $CaCO_3$ matrix.

36 Mn^{54}, Zn^{65}

Laboratory, California (Harrison 1969)

Anodonta nuttalliana was exposed to waterborne radionuclides for 147 days. Concentrations reached equilibrium after about 100 days in some soft tissues. Accumulation rates depended on concentration, and were greater at the higher temperatures and for the smaller specimens tested. Calcareous tissue was the main storage site in the body.

37 Sr^{85}

Pond, Cincinnati, Ohio (Brungs 1965)

Anodonta grandis and *Lampsilis radiata siliquoidea* exposed to Sr^{85} in water reached equilibrium in 80 days. Concentrations of Sr^{85} were higher in soft parts than in shells, and higher in the young of each species than in the adults. Sr^{85} values have no real meaning unless Ca content of the organism or its surrounding environment is known.

38 Sr^{90}

Tennessee River System, Tennessee (Nelson 1962, 1964)

Unionids concentrated Sr^{90} in shells and may be useful as indicators for its detection. Concentrations in water could be predicted for 800 km downstream on the basis of dilution factors. Concentrations ranged from 150 to 550 ppm, depending on species, age, and growth rate.

Table 1. *Continued.*

39 Sr, Sr^{90}

Lake Pepin on Mississippi River, Minnesota (Pahl 1969)

In *Lampsilis ventricosa* collected alive, one analysis of the shells showed that concentrations of stable Sr were 10 orders of magnitude greater than those of Sr^{90}. Annual layers of shells could be used to correlate fallout and uptake of Sr^{90}. *L. ventricosa* is a valid indicator of Sr^{90} fallout.

40 Tc^{99}

Alsea River, Oregon (Hevland 1981)

The whole-body concentration factor was 0.9 for Tc^{99} in *Margaritifera margaritifera*. This element was neither extensively concentrated nor tenaciously retained. Uptake and elimination are probably passive.

41 Zn

River Murray, South Australia (Millington and Walker 1983)

At concentrations of 20 mg/L or more, *Velesunio ambiguus* avoided taking up Zn by significantly curtailing siphon action. The 336-h LC50 was 66 mg/L.

42 Zn^{65}

Columbia River, Washington (Pauley and Nakatani 1968)

Anodonta californiensis showed a continuing accumulation of Zn^{65} throughout the 36-day experiment. Final body burdens were about 100 μCi in soft tissue and 300 μCi in the shell. Gills contained 0.42 mg/g of wet tissue, mantle and palps 0.08, body mass 0.044, adductor 0.035, and foot 0.033.

Laboratory, Cadarache, France (Foulquier et al. 1973)

Anodonta cygnea accumulated Zn^{65} rapidly (the peak was on the third or fourth day) but lost it slowly over 31 days. In an aquarium containing sediment, Zn^{65} partitioned from the water into the sediment; after 59 days 93.6% of the Zn^{65} was in the sediment, 6.2% in *A. cygnea*, and only 0.2% in the water. Concentration factors were 7,240 in gills, 3,140 in siphons, 2,880 in mantle edge, and 230 in shell.

Pesticides

Aminocarb

Laboratory, New Brunswick, Canada (McLeese et al. 1980)

Anodonta cataractae was resistant to aminocarb; it was not killed at the highest concentration tested (5 mg/L). Relative sensitivity of organisms was as follows: marine crustaceans > salmon > bivalves.

Antimycin

Laboratory, Madison, Wisconsin (Antonioni 1974)

After *Elliptio dilatatus* and *Lampsilis siliquoidea* were exposed to the piscicide antimycin for 27 days at 17, 22, and 27 °C, die-off increased with increasing temperatures at 12 and 15 ppb of antimycin, but not at 5 or 10 ppb. The die-off was not immediate, but delayed. *L. siliquoidea* was more sensitive than *E. dilatatus.*

Ashippun River, Wisconsin (Flowers et al. 1975)

Antimycin was applied at six concentrations along a 3.2-km stretch of the river to assess mortality of mussels. At concentrations of 7 to 42 ppb, a die-off that varied in severity with species and water temperature occurred over a 2-month period. Relative mortality of mussel fauna was Lampsilinae > Anodontinae > Unioninae.

Flint River and Laboratory, Warm Springs, Georgia (Marking and Chandler 1978)

Corbicula leana and *Magnonaias boykiniana* exposed to antimycin at concentrations used in field applications survived post-observation periods in holding ponds. Exposure of *C. leana* for 30 days to 3.6–30 μg/L of antimycin resulted in latent mortality. A single treatment of 2 μg/L in an earthen pond resulted in no significant mortality in *C. leana*, but 65% mortality in *M. boykiniana*, within 22 weeks.

Chlordane, dieldrin, polychlorinated biphenyls (PCB's), and 1,1,1-trichloro-2,2-bis(p-chlorophenyl)ethane (DDT)

Humber River, Rexdale, Ontario (Curry 1977/78)

Elliptio complanata that contained contaminants below detection levels accumulated significant concentrations in soft tissues after 28 days of exposure in cages in the Humber River: more than 2.0 ppb of chlordane, 1.0 ppb of dieldrin, 60 ppb of PCB's, and 6 ppb of DDT. Caged *E. complanata* proved practical for detecting organic trace contaminants in water after a short exposure period.

Table 1. *Continued.*

Dichlorodiphenyltrichloroethane (DDT)

Columbia River, Oregon/Washington (Claeys et al. 1975)

Concentrations of DDT in *Anodonta* sp. ranged from 14.9 ppb in spring to 2 ppb in fall.

Laboratory, Delphi, India (Pillai et al. 1980)

The maximum concentration of total DDT in *Indonaia caerulea* exposed to 0.005, 0.01, and 0.05 ppm of DDT in water was 3.42, 3.29, and 9.75 ppm, respectively. Clams transferred to fresh water eliminated about 30% of the DDT in 24 h and 70% in 11 days.

Dichlorodiphenyltrichloroethane (DDT) and dieldrin (HEOD)

Laboratory, Lansing, Michigan (Bedford and Zabik 1973)

Anodonta grandis, Elliptio dilatata, and *Lampsilis siliquoidea* concentrated DDT about 2,400-fold and dieldrin 1,200-fold above waterborne concentrations in lake water. The insecticides were taken up and eliminated more rapidly in lake water than in distilled water. Residues were highest in digestive and reproductive tissues and lowest in muscle, mantle, and gill tissues.

Diazinon-C^{14} and Parathion-S^{35}

Laboratory, East Wareham, Massachusetts (Miller et al. 1966)

Elliptio complanatus, exposed to insecticides in a cranberry bog during field applications, accumulated the insecticides to levels higher than those in water. The insecticides were metabolized faster by fish than by mussels. Most chemicals disappeared from the water within 6 days.

Dieldrin

Laboratory, Columbus, Ohio (Fikes and Tubb 1971, 1972)

Amblema plicata exposed to 20 ppb of dieldrin concentrated it in gill tissue to 1,000 times the waterborne levels during 2 weeks of exposure. The levels declined at one-sixth of the uptake rate when the organisms were placed in untreated water. *A. plicata* is an acceptable monitor for the detection of dieldrin contamination in streams.

Endrin

Laboratory, Victoria, Australia (Ryan et al. 1972)

Hydrella australis was an excellent organism for use in monitoring concentrations of endrin in fresh water. Tissue concentrations were 0.38 ppm after 24 days of exposure and 0.05 ppm after 68 days of withdrawal.

Fenitrothion

Laboratory, New Brunswick, Canada (McLeese et al. 1979)

Fenitrothion was readily taken up, but excreted even faster, by *Anodonta cataractae*. Water concentrations of 0.00083 mg/L or less are not likely to result in significant contamination of this species.

Insecticides

Laboratory, Hungary (Salanki and Varanka 1978)

Anodonta cygnea responded to exposures to sublethal concentrations of Dimecron-50, Hungaria L-7, Satox 20, and Thimet-106 by shortening the pumping period. Thimet and Satox were lethal at 0.1 g/L and 1 mL/L, respectively. Monitoring of pumping activity of mussels may enable detection of water pollution by insecticides.

Lampricides

Laboratory, Michigan (Maki et al. 1975)

The 96-h LC50 for 3-trifluoromethyl-4-nitrophenol (TFM) to *Ligumia* sp. was 8.3 mg/L for individuals up to 9 cm long and 11.7 mg/L for those longer than 16 cm. The 24-h LC50 ranged from 1.5 to 4 times the determined stream concentration of 9.0 mg/L. Sensitivity to TFM was greater in the younger than in the older life stages of *Ligumia* sp.

Muskegon River, Michigan (Maki and Johnson 1976)

Anodonta sp. concentrated the lampricide TFM by 3 to 4 times the water concentrations during a 24-h exposure. Average residue concentrations (μg/g, wet weight) were 44.4 in foot, 38.5 in the viscera, and 37.7 in gill. Average half-time for residue elimination was 20.2 h.

Laboratory, Hammond Bay, Michigan (Rye and King 1976)

For *Elliptio dilatatus*, the LC50 was 0.382 ppm for the lampricide Bayer 73 and 4.7 ppm for TFM plus 2% Bayer 73. This mussel was about as sensitive as rainbow trout (*Salmo gairdneri*) but much more resistant than sea lampreys (*Petromyzon marinus*).

Table 1. *Continued.*

Malathion

Laboratory, Tirupati, India (Kabeer Ahamad et al. 1979)

Rate of ciliary activity of *Lamellidens marginalis* was inhibited by 5.0 mg/L of malathion, and depended on concentration, time, and temperature.

Organochlorines

Red Cedar River, Michigan (Bedford et al. 1968)

Anodonta grandis, Lampsilis siliquoidea, and *L. ventricosa* placed in six locations accumulated DDT and its metabolites; the rate of accumulation increased with exposure time. Methoxychlor was detected regularly in mussels in the lower river section; aldrin was detected on only two sampling dates. Mussels were considered useful for monitoring pesticides that were otherwise undetectable.

Five rivers in Mississippi (Leard et al. 1980)

Seven mussel species and water from five rivers were monitored for pesticides over a 2-year period. Methyl parathion and toxaphene were found in areas of high agricultural use. Significant reductions in DDT were noted in 1973, after widespread use of the pesticide was banned. The accumulation of pesticides by the mussels varied among species.

Rotenone

Laboratory, La Crosse, Wisconsin (Farringer 1972)

When rotenone (Noxfish) was tested against aquatic invertebrates in laboratory toxicity tests, the 96-h LC50 for *Lampsilis* sp. was 2.7 mg/L in soft water and 2.3 mg/L in hard water; values for fish are much lower.

Miscellaneous

Acid mine drainage

North Anna River, Virginia (Simmons and Reed 1973)

Freshwater mussels did not inhabit stream areas polluted with mining wastes, even though the physical habitat appeared suitable. Avoidance of these areas could also have been caused by siltation or lack of suitable host fish.

Ammonia

Laboratory, Illinois (Anderson et al. 1978)

Ciliary response of *Elliptio complanata* decreased linearly with increasing concentrations of un-ionized ammonia. The reduction was 50% at 0.06 mg/L. Sphaeriidae were more sensitive than *E. complanata* to ammonia.

Blanco River, Texas (Horne and McIntosh 1979)

An ammonia concentration of 5 mg/L was lethal to 40% of *Amblema p. plicata* and *Anodonta g. grandis* in 7 days. Ammonia is sometimes lethal to mussels in water, even though oxygen levels are not low enough to indicate pollution. *Corbicula* sp. was more resistant and *Amblema p. plicata* less resistant than other mussels to stresses associated with sewage effluents.

Crude oil, naphthalene, toluene

Auke Lake, Auke Bay, Alaska (Moles 1980)

Fry of coho salmon (*Oncorhynchus kisutch*) exposed to different numbers of glochidia of *Anodonta oregonensis* were more sensitive than uninfected fish to each toxicant. Sensitivity increased linearly with increasing parasitism, and first became significant in fry bearing 20-35 glochidia.

Phenol

Ponds near Borok, U.S.S.R. (Alekseyev and Antipin 1976)

For *Anodonta complanata*, the LC100 for phenol was 700 mg/L, and the LC50 was 500 mg/L. Mollusks were more resistant than crustaceans to phenols.

Polychlorinated biphenyl (PCB)

Columbia River, Oregon and Washington (Claeys et al. 1975)

Anodonta sp. contained 35-160 μg/kg wet weight of PCB's. *Corbicula* sp. accumulated far more PCB's (390-1,170 μg/kg) than did other mollusks.

Table 1. *Continued.*

Pool 15, Mississippi River (U.S. Army Corps of Engineers 1984)
Ranges in concentrations of PCB residues (μg/kg, wet weight) were 20-110 for *Megalonaias gigantea*, 30-67 for *Proptera alata*, 30-35 for *Amblema plicata*, and 20-65 for *Quadrula* sp.
Polynuclear aromatic hydrocarbons (PAH)
Lake George, New York (Heit et al. 1980)
Polynuclear aromatic hydrocarbons were detected in mussels; however, concentrations were not given.
Sand, silt
Laboratory, La Crosse, Wisconsin (Marking and Bills 1980)
Lampsilis radiata luteola and *Fusconaia flava* exposed to overlays of sand or silt in the laboratory either emerged within a few hours or died. Overlays 18 cm thick or thicker were required to prevent emergence of *L. r. luteola*, but those only 10 cm thick prevented emergence of 50% of the *F. flava*. Mussels situated in horizontal positions were less able to emerge than were those in normal upright positions.
Strip mine waste
Cumberland River Basin, Kentucky and Tennessee (Call and Parmalee 1981)
Continued survival of *Alasmidonta atropurpurea* was uncertain because of threatening strip mine waste. Coal mining operations were degrading some streams within the river basin.
Textile and sewage wastes
Tallapoosa and Chattahoochee river systems, Alabame (Jenkinson 1979)
Unionid clams were incapable of surviving and reproducing in polluted streams inhabited by *Corbicula* sp. The exotic *Corbicula* sp. is now considered a dominant member of many North American freshwater mussel faunas.

wrote that Mn was not essential for respiratory function, contradicting the opinion expressed by Pelseneer (1935, as cited by Ravera 1964).

Other metals are concentrated by different tissues in about the same relative order (e.g., concentrations were frequently highest in the gills), but in lesser quantities—as exemplified by concentrations (ppm) reported by Forester (1980) in soft tissues of *A. grandis*: Al, 1,500; Zn, 200; Pb, 18; Cd, 17; Cu, 6; and Ni, 1.2. Leatherland and Burton (1974) reported that levels of Cd in *A. cygnea* were about 19 times greater in the River Thames (9 ppm, dry weight) than in the largely unpolluted River Test (0.49 ppm).

Although Zn was not highly toxic, it did curtail siphon activities of naiades exposed to concentrations of 20 mg/L or greater (Millington and Walker 1983). Price and Schiebe (1978), who measured the velocity at which water is siphoned by naiades, concluded that a knowledge of the volume of water passed through the gill filaments is important in evaluating the accumulation of trace metals. Naiades are rather sensitive to sulfhydryl blocking agents (Hg, Cd), which caused a marked shortening of their periods of activity (Salanki 1979); such a decrease in water filtering might be expected to inhibit growth. In most studies, metals were concentrated more rapidly in the soft tissues than in the shell; however, concentrations in shell layers were useful for identifying specific years when radioactive fallout entered an aquatic ecosystem (Pahl 1969; Pruiskma et al. 1981). Metals were readily eliminated from the soft tissues, but were stable in the shell.

Tessier et al. (1984), who studied partitioning of metals in *Elliptio complanata*, found that Cu, Pb, and Zn levels in various tissues were related to extractability, rather than to total metal concentrations in adjacent sediment. Also, accumulation was influenced by the protective or competitive effect of other sediment constituents. They suggested that bioavailability of contaminants depends on physical, chemical, and biological changes and conditions. Schmitt and Finger (1982), after sampling numerous sites contaminated with lead tailings, reported that levels of metals in mussels were not highest at locations with the highest total sediment concentrations, and that Mn concentrations were unrelated to those in the water.

The numerous reports on accumulation and tissue residues verify that naiad mollusks are useful indicators of past and recent metal contamination and environmental stress in aquatic environments.

Pesticides

Insecticides are readily taken up and eliminated by freshwater mussels in water (Godsil and Johnson 1968). Residues of dieldrin and DDT were highest in digestive and reproductive tissue and lowest in the muscle, mantle, and gill tissues (Bedford and Zabik 1973). Concentrations of DDT in *Anodonta* sp. were higher in spring than in fall (Claeys et al. 1975). Salanki and Varanka (1978) determined that sublethal exposure to pesticides caused a shortening of the pumping (siphoning) period and that the pesticides Thimet and Satox were lethal to *A. cygnea* at 100 and 1,000 ppm, respectively. Varanka (1977, 1978) reported that glochidia of *A. cygnea* were suitable test subjects, and that lasting closure of valves resulted when the glochidia were exposed to high concentrations of some pesticides; if exposed to lower concentrations for longer periods, glochidia may be unable to attach to host fish.

Although various investigators have suggested that freshwater aquatic invertebrate populations are relatively unaffected by acute exposures to fish toxicants (Chandler and Marking 1975; Fremling 1975; Jacobi and Degan 1977), delayed mortality was reported in certain species of naiades as a result of acute exposure to antimycin (Antonioni 1974). Maki et al. (1975) reported that the lampricide 3-trifluoromethyl-4-nitrophenol (TFM) was not toxic to adult *Ligumia* sp. at stream treatment concentrations but that earlier life stages were more sensitive. Fish toxicants do not appear to be a serious threat to the naiad fauna; however, the long-term effects of piscicides on naiad populations have not been fully assessed.

Pesticides are suspected of being responsible for the decline of naiades in Illinois (Klippel and Parmalee 1979). After a single application of rotenone to an impoundment in Florida, populations of *A. peggyae* dwindled drastically and *A. imbecillis* became nearly extinct (Heard 1970). However, in standardized laboratory tests, Farringer (1972) reported that rotenone was less toxic to *Lampsilis* sp. than to fish.

Other Contaminants

Ammonia decreased ciliary action in *Elliptio complanata* at a concentration of 0.06 ppm (Anderson et al. 1978). No living naiades were found in the upper Illinois River where ammonia nitrogen exceeded 6 ppm, but began to appear downstream where the levels became progressively lower (Starrett 1971). A concentration of 5 ppm of ammonia was lethal to 40% of *Amblema p. plicata* and *Anodonta g. grandis* in 7 days (Horne and McIntosh 1979); *Corbicula* sp. was more resistant than native species.

Anodonta sp. contained 35–160 μg/kg, wet weight, of PCB's, and far more PCB's were accumulated by *Corbicula* sp. than by other mollusks (Claeys et al. 1975). PCB concentrations ranged from 20 μg/kg (the level of detection) to 110 μg/kg (wet weight) in soft tissues of *Megalonaias gigantea*, *Proptera alata*, *Amblema plicata*, and *Quadrula* sp. from Pool 15 of the Mississippi River (U.S. Army Corps of Engineers 1984).

Although concentrations of contaminants in mining wastes were not quantified, naiades avoided polluted areas even though the physical habitat, other than the water, was suitable (Simmons and Reed 1973; Morris and Taylor 1978). Other factors, in addition to pesticides, were assumed to be responsible for depleting entire naiad communities in the lower Minnesota River and in northern Missouri (Fuller 1978; Oesch 1984).

Discussion

Naiad mollusks are important environmental indicators of water quality of river systems and lakes; their absence has been considered an indication of environmental stress. The factors known or suspected to adversely affect their populations include waterway modification, streambed change, commercial barge activities, sedimentation, commercial mussel fishing, absence of host fish, competition from the exotic Asiatic clam, and the presence of contaminants that result from agricultural runoff or municipal or industrial processes.

Early work of Ortmann (1909) and Baker (1928) identified chemical pollution as a primary reason for the disappearance of naiad mollusks from entire sections of major river systems. Ingram (1956) noted that little was known about the effects of contaminants on glochidia, and Imlay (1982) noted the paucity of information on the uptake of metals. Fuller (1980*a*) identified sections of the Upper Mississippi River that did not sup-

port thriving naiad populations, and reported that the specific contaminants and causes responsible for the deteriorated condition had not been identified. The decline in molluscan fauna can be expected to continue unless the causes are identified, and corrective measures are taken to create more favorable conditions.

Marking et al. (1981), who examined sediments from 10 Minnesota locations on the Upper Mississippi River, extending from Winona to St. Paul, classified samples from the commercial harbor at Redwing and the St. Paul barge terminal as heavily polluted on the basis of contaminant content; concentrations of Cr, Cu, Fe, Pb, and Zn were notably higher at these sites than at others. Since naiades accumulate these elements at concentrations equal to or exceeding those in the sediment, and concentrations of individual elements in sediments at these sites of enrichment are not acutely lethal, we assume that the scarcity of mussels in these zones is due to the combined effects of all contaminants and physiological stresses. Areas of metal enrichment in the Upper Mississippi River reported by Wiener et al. (1984) and Bailey and Rada (1984) coincided with the "unhealthy" zones reported by Fuller (1980*a*).

Many factors affect naiades and their habitats. Usually more than one factor contributes to the total impact, but few investigators have studied cumulative effects. For instance, municipal effluent may contribute a sublethal concentration of ammonia to a river that already contains significant quantities of metals from industrial processes upstream. Naiades may be able to thrive in stream water containing only the metals or only the ammonia, but not in water containing both. Additional factors may add even more stress; high temperatures or decreasing pH may increase the toxicity of ammonia and metals. Even high temperature alone is sometimes lethal (Salbenblatt and Edgar 1964). The composition and size of the naiad fauna can seldom be associated with a specific disruption (Fuller 1974). Bauer et al. (1980) concluded that the cause of a more than 90% decrease of *Margaritifera margaritifera* in central Europe since the early 1900's was probably due to eutrophication rather than to the presence of trace metals. Taylor (1980) stated that the loss of naiad fauna in the upper Ohio River was not attributable to any one factor, but that combinations of stresses were responsible. Recovery of naiad populations in a section of the Green River, Kentucky, that was heavily polluted by oil field brine in 1958 suggests that pollution abatement programs may be effective in reestablishing populations (Williams 1969).

Measurement of the concentrations of pollutants in water and sediments seldom yields a valid indication of the ultimate threat to the ecosystem (Forester 1980). An alternative is to collect and analyze living organisms to establish indices of the biological availability of contaminants and to integrate the changing levels in the environment by monitoring those levels over an extended period (Forester 1980). Mouthon (1981), for example, correlated patterns of sensitivity to pollution by five species with biotic characteristics that tended to restrict their distribution. Caged mussels proved practical for detecting contaminants after only 8 days of exposure (Curry 1977/78). Rosenberg and Henschen (1984) used electron microprobe analyses of stains in shells to illustrate that they are useful indicators of water quality. The index for measuring impacts of pollution has largely concerned observations of the elimination of single species or populations, or the destruction of habitat and entire ecosystems.

Forester (1980) noted that about 19 metals and trace elements, 36 radionuclides, and 17 organic compounds formed appreciable residues in mussel tissues, in which they were accumulated to levels several orders of magnitude greater than those in the water. Several authors noted metals and organochlorines in tissue where they were not detected in surface waters. Residues in soft parts generally reflect present levels of contaminants in sediments and water; past contamination, especially radionuclide fallout, is reflected in the respective annual growth layers of the shell (Pahl 1969). Particular naiad organs, especially gills or the calcareous tissue near the gill attachment, have been shown to be useful in monitoring contaminants (Harrison 1966, 1969; Adams et al. 1981; Salanki et. al. 1982). Some investigators considered other tissues useful, such as those of the digestive and reproductive systems. Stein (1973) suggested that the most important role of *Amblema plicata* may well be that of an aquatic environmental monitor. Brungs (1967), Harrison (1969), Maki et al. (1975), and Price and Knight (1978) were among those who found concentrations of metals to be higher in small (presumably young) specimens than in

large ones. However, Manly and George (1977) found that concentrations in naiades from the same locality were not closely related to size, but were highly variable among individuals—especially in immature specimens.

Among the numerous reports of contaminants and their effects on naiades that we reviewed, only a few provided enough specific information to relate quantities of contaminants in tissue to environmental levels or hazards. Most of the data were nonquantitative, and in many reports the conditions of tests were not fully reported, nor were procedures standardized. Generally, in laboratory tests, the sample sizes were inadequate and replication was lacking.

Various suggestions have been made for improvements. The International Mussel Watch (National Research Council 1980) suggested that 25 mussels of a species are required to provide adequate representation of a population for a chemical assay. Specific methodologies and standardized procedures were also treated by Lord et al. (1977) and Sterrett and Saville (1974). Duncan and Thiel's (1983) study of age, density, diversity, and distribution of naiades in Pool 10 of the Upper Mississippi River should be a useful guide to researchers. Forester (1980) suggested criteria for testing methods that should make future studies more useful.

The continued existence of healthy populations of naiades in river systems will require that three precautions be taken: (1) more qualitative and quantitative analyses must be made of the effects of contaminants, in addition to and in conjunction with other factors that adversely affect these populations; (2) extensive monitoring programs are needed to identify the sources and effects of contaminants; and (3) commitments must be made by resource managers and regulating agencies to eliminate or reduce these sources and effects.

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References

Adams, T. G., G. J. Atchison, and R. J. Vetter. 1981. The use of the three-ridge clam (*Amblema perplicata*) to monitor trace metal contamination. Hydrobiologia 83:67–72.

Alekseyev, V. A., and B. N. Antipin. 1976. Toxicological characteristics and symptons of acute phenol poisoning in some freshwater crustaceans and mollusks. Hydrobiol. J. 12:27–33.

Anderson, K. B., R. E. Sparks, and A. A. Paparo. 1978. Rapid assessment of water quality using the fingernail clam, *Musculium transversum*. University of Illinois, Water Resources Center, Urbana. UILU-WRC-78-0133. Res. Rep. 133. 115 pp.

Anderson, R.V. 1977. Concentration of cadmium, copper, lead, and zinc in six species of freshwater clams. Bull. Environ. Contam. Toxicol. 18:492–496.

Antonioni, M. E. 1974. Antimycin—beyond teleocide. Wis. Acad. Sci. Arts Lett. 62:285–301.

Athearn, H. 1967. Changes and reductions in our freshwater molluscan populations. Am. Malacol. Union, Inc. Annu. Rep. 1967:44–45.

Bailey, P. A., and R. G. Rada. 1984. Distribution and enrichment of trace metals (Cd, Cr, Cu, Ni, Pb, Zn) in bottom sediments of navigation Pools 4 (Lake Pepin), 5, and 9 of the Upper Mississippi River. Pages 119-138 *in* J. G. Wiener, R. V. Anderson, and D. R. McConville, eds. Contaminants in the Upper Mississippi River. Butterworth Publishers, Boston, Mass.

Baker, F. C. 1922. The molluscan fauna of the Big Vermilion River, Illinois. Ill. Biol. Monogr. 7:1–126.

Baker, F. C. 1928. The fresh water Mollusca of Wisconsin. Part II. Pelecypoda. Bull. Wis. Geol. Nat. Hist. Surv. 70:1–495.

Bates, J., and S. D. Dennis. 1976. Mussels and the law. Page 2 *in* North Am. Betholog. Soc. Titles Abstr.

Bauer, G., E. Schrimpff, W. Thomas, and R. Herrmann. 1980. Relations between the decline of the freshwater pearl mussel (*Margaritifera margaritifera*) in the Fichtelgebirge and the water quality. Arch. Hydrobiol. 88:505–513.

Bedford, J. W., E. W. Roelofs, and M. J. Zabik. 1968. The freshwater mussel as a biological monitor of pesticide concentrations in a lotic environment. Limnol. Oceanogr. 13:118–126.

Bedford, J. W., and M. J. Zabik. 1973. Bioactive compounds in the aquatic environment: uptake and loss of DDT and dieldrin by freshwater mussels. Arch. Environ. Contam. Toxicol. 1:97–111.

Bradley, H. C. 1907*a*. The occurrence of manganese in the freshwater clam. Science 25:456.

Bradley, H. C. 1907*b*. Manganese, a normal element in the tissues of the fresh water clams, *Unio* and *Anodonta*. J. Biol. Chem. 3:151–157.

Bradley, H. C. 1910. Manganese of the lamellibranchs. Biol. Bull. 19:161-166.

Brungs, W. A. 1965. Experimental uptake of strontium-85 by freshwater organisms. Health Phys. 11:41–46.

Brungs, W. A., Jr. 1967. Distribution of cobalt 60, zinc 65, strontium 85, and cesium 137 in a freshwater pond. U.S. Public Health Serv. Publ. 999-RH-24. 52 pp.

Call, S. M., and P. W. Parmalee. 1981. The discovery of extant populations of *Alasmidonta atropurpurea*

(Rafinesque) (Bivalvia: Unionidae) in the Cumberland River Basin. Bull. Am. Malacol. Union Inc. 1981:42-43.

Chandler, J. H., and L. L. Marking. 1975. Toxicity of the lampricide 3-trifluoromethyl-4-nitrophenol (TFM) to selected aquatic invertebrates and frog larvae. U.S. Fish Wildl. Serv., Invest. Fish Control 62:1-7.

Chin, H. C., and F. F. Chou. 1978. Acute toxicity of chromium to the freshwater mussel, *Hyriopsis cumingii* Lea. Nan-ching Ta Hsueh Hsueh Pao, Tzu Jan K'o Hsueh 4:96-101.

Claeys, R. R., R. S. Caldwell, N. H. Cutshall, and R. Holton. 1975. Chlorinated pesticides and polychlorinated biphenyls in marine species, Oregon/Washington coast 1972. Pestic. Monit. J. 9:2-10.

Curry, C. A. 1977/78. The freshwater clam (*Elliptio complanata*), a practical tool for monitoring water quality. Water Pollut. Res. Can. 13:45-52.

Czarnezki, J. M. 1983. The use of the pocketbook mussel for monitoring heavy metal pollution in an Ozark stream. Page 27 *in* 31st Annu. Meet. North Am. Bentholog. Soc. (Abstract).

Dawley, C. 1947. Distribution of aquatic mollusks in Minnesota. Am. Midl. Nat. 38:671-697.

Dineen, C. F. 1971. Changes in the molluscan fauna of the Saint Joseph River, Indiana, between 1959 and 1970. Proc. Indiana Acad. Sci. 80:189-195.

Duncan, R. E., and P. A. Thiel. 1983. A survey of the mussel densities in Pool 10 of the Upper Mississippi River. Wis. Dep. Nat. Resour. Tech. Bull. 139. 14 pp.

Ecological Analysts, Inc. 1981. Survey of freshwater mussels (Pelecypoda: Unionacea) at selected sites in Pools 11 through 24 of the Mississippi River. Ecological Analysts, Inc., Northbrook, Ill. EA Rep. 9031. 188 pp.

Ellis, M. M. 1931*a*. A survey of conditions affecting fisheries in the Upper Mississippi River. U.S. Bur. Fish. Circ. 5:1-18.

Ellis, M. M. 1931*b*. Some factors affecting the replacement of the commercial fresh-water mussels. U.S. Bur. Fish. Circ. 7:1-10.

Ellis, M. M. 1936. Erosion silt as a factor in aquatic environments. Ecology 17:29-42.

Ellis, M. M. 1937. Detection and measurement of stream pollution. Bull. U.S. Bur. Fish. 22:365-437.

Farringer, J. E. 1972. The determination of the acute toxicity of rotenone and Bayer 73 to selected aquatic organisms. M.S. thesis, University of Wisconsin-La Crosse. 32 pp.

Fikes, M. H., and R. A. Tubb. 1971. *Amblema plicata* as a pesticide monitor. Pages 34-37 *in* S. E. Jorgensen and R. W. Sharp, eds. Proceedings of the symposium on rare and endangered mollusks (naiads) of the U.S. U.S. Fish Wildl. Serv., Bur. Sport Fish. Wildl., Twin Cities, Minn.

Fikes, M. H., and R. A. Tubb. 1972. Dieldrin uptake in the three-ridge naiad. J. Wildl. Manage. 36:802-809.

Flowers, R. W., R. M. Johnson, and W. L. Hilsenhoff. 1975. Effects of antimycin on instream mussel populations. Wis. Dep. Nat. Resour. Res. Rep. 84. 11 pp.

Forester, A. J. 1980. Monitoring the bioavailability of toxic metals in acid-stressed shield lakes using pelecypod molluscs (clams, mussels). Proc. Univ. Mo. Annu. Conf. Trace Subst. Environ. Health 14:142-147.

Foster, R. B., and J. M. Bates. 1978. Use of freshwater mussels to monitor point source industrial discharges. Environ. Sci. Technol. 12:958-962.

Foulquier, L., P. Bovard, and A. Grauby. 1973. Resultats experimentaux sur la fixation du zinc-65 par *Anodonta cygnea* (Linnaeus). Malacologia 14:107-124.

Fox, H. M., and H. Ramage. 1931. A spectrographic analysis of animal tissues. Proc. R. Soc. London B Biol. Sci. 108:157-173.

Fremling, C. R. 1975. Acute toxicity of the lampricide 3-trifluoromethyl-4-nitrophenol (TFM) to nymphs of mayflies (*Hexagenia* sp.). U.S. Fish Wildl. Serv., Invest. Fish Control 58:1-8.

Fuller, S. L. H. 1974. Clams and mussels (Mollusca: Bivalvia). Pages 215-273 *in* C. W. Hart, Jr. and S. L. H. Fuller, eds. Pollution ecology of freshwater invertebrates. Academic Press, New York.

Fuller, S. L. H. 1978. Fresh-water mussels (Mollusca: Bivalvia: Unionidae) of the Upper Mississippi River: observations at selected sites within the 9-foot channel navigation project on behalf of the United States Army Corps of Engineers. Academy of Natural Sciences, Philadelphia, Pa. 401 pp.

Fuller, S. L. H. 1980*a*. Historical and current distributions of fresh-water mussels (Mollusca: Bivalvia: Unionidae) in the Upper Mississippi River. Pages 72-119 *in* J. L. Rasmussen, ed. Proceedings of the symposium on Upper Mississippi River bivalve mollusks. Upper Mississippi River Conservation Committee, Rock Island, Ill.

Fuller, S. L. H. 1980*b*. Freshwater mussels (Mollusca: Bivalvia: Unionidae) of the Upper Mississippi River: observations at selected sites within the 9-foot navigation channel project for the St. Paul District, United States Army Corps of Engineers, 1977-1979. Academy of Natural Sciences, Philadelphia, Pa. Vol. 1. 175 pp.

Gabay, J. J., J. A. Dapolito, and N. I. Sax. 1966. ^{54}Mn in freshwater clams. Health Phys. 12:968-970.

Gaglione, P., and O. Ravera. 1964. Manganese-54 concentration in fall-out, water, and *Unio* mussels of Lake Maggiore, 1960-1963. Nature (Lond.) 204:1215-1216.

Garder, K., and O. Skulberg. 1965. Radionuclide accumulation by *Anodonta piscinalis* Nilsson (Lamellibranchiata) in a continuous flow system. Hydrobiologia 26:151-169.

Gardner, W. S., W. H. Miller III, and M. J. Imlay. 1981. Free amino acids in mantle tissues of the bivalve *Amblema plicata*: possible relation to environmental stress. Bull. Environ. Contam. Toxicol. 26:157-162.

Godsil, P. J., and W. C. Johnson. 1968. Pesticide monitoring of the aquatic biota at the Tule Lake National Wildlife Refuge. Pestic. Monit. J. 1:21-26.

Gordon, M. E. 1982. Mollusca of the White River, Arkansas and Missouri. Southwest. Nat. 27:347-352.

Grasse, P. P. 1960. Traite de Zoologie, Vol. 5. Mollusques. Masson, Paris. 2133 pp.

Harrison, F. L. 1966. Metabolism of Mn^{54} and other cations in the fresh-water clam. Physiologist 9:200.

Harrison, F. L. 1969. Accumulation and distribution of ^{54}Mn and ^{65}Zn in freshwater clams. Pages 198-220 *in* D. J. Nelson, F. C. Evans, S. I. Auerbach, P. B. Dunaway, F. F. Hooper, E. J. Kuenzler, T. R. Rice, C. A. Tryon, and R. G. Wiegert, eds. Proceedings of the second national symposium on radioecology. U.S. Atomic Energy Commission Conference 670503.

Harrison, F. L., and D. J. Quinn. 1972. Tissue distribution of accumulated radionuclides in freshwater clams. Health Phys. 23:509-517.

Harvey, R. S. 1969. Uptake and loss of radionuclides by the freshwater clam *Lampsilis radiata* (Gmel.). Health Phys. 17:149-154.

Havlik, M. E. 1983. Naiad mollusk populations (Bivalvia: Unionidae) in Pools 7 and 8 of the Mississippi River near La Crosse, Wisconsin. Am. Malacol. Union Inc. Bull. 1:51-60.

Havlik, M. E., and D. H. Stansbery. 1977. The naiad mollusks of the Mississippi River in the vicinity of Prairie du Chien, Wisconsin. Bull. Am. Malacol. Union, Inc. 1977:9-12.

Heard, W. H. 1970. Eastern freshwater mollusks. II. The South Atlantic and Gulf drainages. Malacologia 10:23-31.

Heit, M., C. S. Klusek, and K. M. Miller. 1980. Trace element, radionuclide, and polynuclear aromatic hydrocarbon concentrations in Unionidae mussels from northern Lake George. Environ. Sci. Technol. 14:465-468.

Hevland, M. E. 1981. Radiotechnetium as an environmental contaminant: metabolism by two freshwater species, the pearl mussel (*Magaritifera margaritifera*) and the rough-skinned newt (*Taricha granulosa*). M.S. thesis, Oregon State University, Corvallis.

Higgins, F. 1858. A catalogue of the shell-bearing species inhabiting the vicinity of Columbus, Ohio, with some remarks thereon. Ohio State Board Agric. Annu. Rep. 12(1857):548-555.

Horne, F. R., and S. McIntosh. 1979. Factors influencing distribution of mussels in Blanco River of central Texas. Nautilus 93:119-133.

Imlay, M. J. 1971. Bioassay tests with naiads. Pages 38-41 *in* S. E. Jorgensen and R. W. Sharp, eds. Proceedings of the symposium on rare and endangered mollusks (naiads) of the U.S. U.S. Fish Wildl. Serv., Bur. Sport Fish. Wildl., Twin Cities, Minn.

Imlay, M. J. 1973. Effects of potassium on survival and distribution of freshwater mussels. Malacologia 12:97-113.

Imlay, M. J. 1980. The use of bio-assay techniques to assess the impacts of environmental change on the mollusk resource. Pages 33-42 *in* J. L. Rasmussen, ed. Proceedings of the symposium on Upper Mississippi River bivalve mollusks. Upper Mississippi River Conservation Committee, Rock Island, Ill.

Imlay, M. J. 1982. Use of shells of freshwater mussels in monitoring heavy metals and environmental stresses: a review. Malacol. Rev. 15:1-14.

Ingram, W. M. 1956.Use and value of biological indicators of pollution: fresh water clams and snails. Pages 94-135 *in* C. M. Tarzwell, ed. Biological problems in water pollution. Robert A. Taft Sanitary Engineerng Center, Cincinnati, Ohio.

Isom, B. G. 1969. The mussel resource of the Tennessee River. Malacologia 7:397-425.

Jacobi, G. Z., and D. J. Degan. 1977. Aquatic macroinvertebrates in a small Wisconsin trout stream before, during, and two years after treatment with the fish toxicant antimycin. U.S. Fish Wildl. Serv., Invest. Fish Control 81:1-24.

Jenkinson, J. J. 1979. The occurrence and spread of *Corbicula manilensis* in east-central Alabama. Nautilus 93:149-153.

Johnson, V., N. Cutshall, and C. Osterberg. 1966. Distribution of Hanford induced gamma emitters in a fresh water mollusc: *Anodonta wahlamatensis*. Pages 105-109 *in* J. E. McCauley, ed. Ecological studies of radioactivity in the Columbia River and adjacent Pacific Ocean. Oregon State University, Corvallis.

Jones, W. G., and K. F. Walker. 1979. Accumulation of iron, manganese, zinc, and cadmium by the Australian freshwater mussel *Velesunio ambiguus* (Phillipi) and its potential as a biological monitor. Aust. J. Mar. Fresh. Res. 30:741-751.

Kabeer Ahamad, I., M. Sethuraman, M. R. Begum, and K. V. Ramana Rao. 1979. Effect of malathion on ciliary activity of fresh water mussel, *Lamellidens marginalis* (Lamarck). Comp. Physiol. Ecol. 4:71-73.

Kapkov, V. T. 1973. Toxicity of copper complexes to freshwater mollusks. Translated from Russian by U.S. Army Foreign Science and Technology Center, Charlottesville, Va. NTIS AD-763 967. 5 pp.

Kidder, G. M. 1977. Pollutant levels in bivalves. Scripps Institution of Oceanography, Mussel Watch Program. Environmental Protection Agency Contract R-80421501.

Klippel, W. E., and P. W. Parmalee. 1979. The naiad fauna of Lake Springfield, Illinois: an assessment after two decades. Nautilus 93:189-197.

Leard, R. L., B. J. Grantham, and G. F. Pessoney. 1980. Use of selected freshwater bivalves for monitoring organochlorine pesticide residues in major Mississippi stream systems, 1972-73. Pestic. Monit. J. 14:47-52.

Leatherland, T. M., and J. D. Burton. 1974. The occurrence of some trace metals in coastal organisms with particular reference to the Solent region. J. Mar. Biol. Assoc. UK 54:457-468.

Lewis, J. 1868. Remarks on some of the Mollusca of the valley of the Mohawk. Am. J. Conchol. 4:241-245.

Lord, D. A., W. G. Breck, and R. C. Wheeler. 1975. Trace elements in molluscs in the Kingston Basin. Water Quality Parameters, American Society for Testing and Materials. ASTM Spec. Tech. Publ. 573:95-111.

Lord, D. A., J. W. McLaren, and R. C. Wheeler. 1977. Determination of trace metals in fresh water mussels by atomic absorption spectrometry with direct solid sample injection. Anal. Chem. 49:257-261.

Maki, A. W., L. Geissel, and H. E. Johnson. 1975. Comparative toxicity of larval lampricide (TFM: 3-trifluoromethyl-4-nitrophenol) to selected benthic macroinvertebrates. J. Fish. Res. Board Can. 32:1455-1459.

Maki, A. W., and H. E. Johnson. 1976. The freshwater mussel (*Anodonta* sp.) as an indicator of environmental levels of 3-trifluoromethyl-4-nitrophenol (TFM). U.S. Fish Wildl. Serv., Invest. Fish Control 70:1-5.

Manly, R., and W. O. George. 1977. The occurrence of some heavy metals in populations of the freshwater mussel *Anodonta anatina* (L.) from the River Thames. Environ. Pollut. 14:139-154.

Marking, L. L., and T. D. Bills. 1980. Acute effects of silt and sand sedimentation on freshwater mussels. Pages 204-211 *in* J. L. Rasmussen, ed. Proceedings of the symposium on Upper Mississippi River bivalve mollusks. Upper Mississippi River Conservation Committee, Rock Island, Ill.

Marking, L. L., and J. H. Chandler, Jr. 1978. Survival of two species of freshwater clams, *Corbicula leana* and *Magnonaias boykiniana*, after exposure to antimycin. U.S. Fish Wildl. Serv., Invest. Fish Control 83:1-5.

Marking, L. L., V. K. Dawson, J. L. Allen, T.D. Bills, and J. J. Rach. 1981. Biological activity and chemical characteristics of dredge material from 10 sites on the Upper Mississippi River. U.S. Fish and Wildlife Service, National Fishery Research Laboratory, La Crosse, Wisconsin. Prepared for U.S. Army Corps of Engineers, St. Paul District, St. Paul, Minn. NTIS ADA107276. 146 pp.

Mathis, B. J., and T. F. Cummings. 1973. Selected metals in sediments, water, and biota in the Illinois River. J. Water Pollut. Control Fed. 45:1573-1583.

McCleneghan, K., M. Meinz, D. Crane, W. Seto, and T. Lew. 1981. Toxic substances monitoring program 1980. Calif. State Water Resour. Control Board, Water Qual. Monit. Rep. 81-8TS. 56 pp.

McHargue, J. S. 1924. The significance of the occurrence of copper, manganese, and zinc in shell-fish. Science 60:530.

McHargue, J. S. 1927. The proportion and significance of copper, iron, manganese and zinc in some mollusks and crustaceans. Ky. Acad. Sci. Trans. 2:46-52.

McLeese, D. W., V. Zitko, and D. B. Sergeant. 1979. Uptake and excretion of fenitrothion by clams and mussels. Bull. Environ. Contam. Toxicol. 22:800-806.

McLeese, D. W., V. Zitko, C. D. Metcalfe, and D. B. Sergeant. 1980. Lethality of aminocarb and the components of the aminocarb formulation to juvenile Atlantic salmon, marine invertebrates, and a freshwater clam. Chemosphere 9:79-82.

Mellinger, P. J. 1972. The comparative metabolism of cadmium, mercury and zinc as environmental contaminants in the freshwater mussel, *Margaritifera margaritifera*. Ph.D. thesis, Oregon State University, Corvallis. 129 pp.

Mellinger, P. J. and D. L. Willis. 1973. The metabolism of radiozinc in the freshwater mussel *Margaritifera margaritifera*. Health Phys. 25:336.

Merlini, M., F. Girardi, R. Pietra, and A. Brazzelli. 1965. The stable manganese content of molluscs from Lake Maggiore determined by activation analysis. Limnol. Oceanogr. 10:371-378.

Miller, C. W., B. M. Zuckerman, and A. J. Charig. 1966. Water translocation of diazinon-C^{14} and parathion-S^{35} off a model cranberry bog and subsequent occurrence in fish and mussels. Trans. Am. Fish. Soc. 95:345-349.

Millington, P. J., and K. F. Walker. 1983. Australian freshwater mussel *Velesunio ambiguus* (Philippi) as a biological monitor for zinc, iron, and manganese. Aust. J. Mar. Freshw. Res. 34:873-892.

Moles, A. 1980. Sensitivity of parasitized coho salmon fry to crude oil, toluene, and naphthalene. Trans. Am. Fish. Soc. 109:293-297.

Morris, J. S., and R. W. Taylor. 1978. A survey of the freshwater mussels (Bivalvia: Unionidae) of the Kanawha River of West Virginia. Nautilus 92:153-155.

Mouthon, J. 1981. Les mollusques et la pollution des eaux douces: ebauche d'une gamme de polluosensibilite des especes. Bijdr. Dierk. 51:250-258.

National Research Council. 1980. The international mussel watch. National Academy of Sciences, Washington, D.C. 248 pp.

Nelson, D. J. 1962. Clams as indicators of strontium-90. Science 137:38-39.

Nelson, D. J. 1963. The strontium and calcium relationships in Clinch and Tennessee river mollusks. Pages 203-211 *in* V. Schultz and A. W. Klement, Jr., eds. Proceedings of the first national symposium on radioecology. Reinhold Publishing Corporation, N.Y., and the American Institute of Biological Sciences, Washington, D.C.

Nelson, D. J. 1964. Biological vectors and reservoirs of strontium-90. Nature (Lond.) 203:420.

Oesch, R. D. 1984. Missouri naiades. Missouri Department of Conservation, Jefferson City. 270 pp.

Ortmann, A. E. 1909. The destruction of the fresh-water fauna in western Pennsylvania. Proc. Am. Philos. Soc. 48:90-110.

Pahl, G. 1969. Radioactive and stable strontium analysis of Upper Mississippi River clamshells. Pages 234-239 *in* D. J. Nelson, F. C. Evans, S. I. Auerbach, P. B. Dunaway, F. F. Hooper, E. J. Kuenzler, T. R. Rice, C. A. Tryon, and R. G. Wiegert, eds. Proceedings of the second national symposium on radioecology. U.S. Atomic Energy Commission Conference 670503.

Pauley, G. B., and R. E. Nakatani. 1968. Metabolism of the radioisotope ^{65}Zn in the freshwater mussel *Anodonta californiensis*. J. Fish. Res. Board Can. 25:2691-2694.

Pelseneer, P. 1935. Essai d'Ethologie Zoologique d'apres l'etude des Mollusques. Acad. R. Belg., Brussels, Belgium. (Not seen; from Ravera 1964).

Pillai, M. K. K., P. K. Mittal, and H. C. Agarwal. 1980. Bioaccumulation, metabolism and elimination of DDT by the fresh water clam *Indonaia caerulea* (Lea). Indian J. Exp. Biol. 18:1439-1442.

Price, R. E., and L. A. Knight, Jr. 1978. Mercury, cadmium, lead, and arsenic in sediments, plankton, and clams from Lake Washington and Sardis Reservoir, Mississippi, October 1975-May 1976. Pestic. Monit. J. 11:182-189.

Price, R. E., and F. R. Schiebe. 1978. Measurements of velocity from excurrent siphons of freshwater clams. Nautilus 92:67-69.

Pruiskma, R. T., T. R. Sweet, D. H. Stansbery, and B. K. Hajek. 1981. Determination of manganese in naiad mollusc shells by neutron activation analysis. Environ. Pollut., Ser. B 2:49-57.

Ravera, O. 1964. Distribution of Mn^{54} from fall-out in population of freshwater lamellibranchs (*Unio mancus elongatulus* Pfeiffer). Verh. int. Ver. theor. angew. Limnol. 15:885-892.

Renzoni, A., and E. Bacci. 1976. Bodily distribution, accumulation, and excretion of mercury in a freshwater mussel. Bull. Environ. Contam. Toxicol. 15:366-373.

Rosenberg, G. D., and M. T. Henschen. 1984. The effects of pollution on growth of midwestern mussel shells. Water Resources Research Center, Purdue University, West Lafayette, Ind. 13 pp.

Ryan, S., G. J. Bacher, and A. A. Martin. 1972. The mussel *Hyridella australis* as a biological monitor of the pesticide endrin in fresh water. Search 3:446-447.

Rye, R. P., Jr., and E. L. King, Jr. 1976. Acute toxic effects of two lampricides to twenty-one freshwater invertebrates. Trans. Am. Fish. Soc. 105:322-326.

Salanki, J. 1979. Behavioural studies on mussels under changing environmental conditions. Symp. Biol. Hung. 19:169-176.

Salanki, J., and I. Varanka. 1976. Effects of copper and lead compounds on the activity of the fresh-water mussel. Ann. Inst. Biol. (Tihany) Hung. Acad. Sci. 43:21-27.

Salanki, J., and I. Varanka. 1978. Effect of some insecticides on the periodic activity of the fresh-water mussel (*Anodonta cygnea* L.). Acta Biol. Acad. Sci. Hung. 29:173-180.

Salanki, J., K. V.-Balogh, and E. Berta. 1982. Heavy metals in animals of Lake Balaton. Water Res. 16:1147-1152.

Salbenblatt, J. A., and A. L. Edgar. 1964. Valve activity in fresh-water pelecypods. Pap. Mich. Acad. Sci. Arts Lett. 49:177-186.

Schmitt, C. J., and S. E. Finger. 1982. The dynamics of metals from past and present mining activities in the Big and Black River watersheds, southeastern Missouri. Final report for the U.S. Army Corps of Engineers, St. Louis District, Proj. DACW43-80-A-0109. 153 pp.

Seah, T. C. M., and D. J. Hobden. 1969. Manganese in the fresh water clam. Can. J. Biochem. 47:557-560.

Short, Z. F., R. F. Palumbo, P. R. Olson, and J. R. Donaldson. 1969. The uptake of I^{131} by the biota of Fern Lake, Washington, in a laboratory and a field experiment. Ecology 50:979-989.

Simmons, G. M., Jr., and J. R. Reed, Jr. 1973. Mussels as indicators of biological recovery zone. J. Water Pollut. Control Fed. 45:2480-2492.

Smith, A. L., R. H. Green, and A. Lutz. 1975. Uptake of mercury by freshwater clams (family Unionidae). J. Fish. Res. Board Can. 32:1297-1303.

Stansbery, D. H. 1970. Eastern freshwater mollusks. I. The Mississippi and St. Lawrence River systems. Malacologia 10:9-22.

Stansbery, D. H., and C. B. Stein. 1971. Why naiades (pearly freshwater mussels) should be preserved. Hearing before a subcommittee of the Committee on Government Operation, House of Representatives, 92nd Congress, First Session, 14 June. 1971: 2177-2179.

Starrett, W. C. 1971. A survey of the mussels (Unionacea) of the Illinois River: a polluted stream. Ill. Nat. Hist. Surv. Bull. 30:267-403.

Stein, C. B. 1973. The life history of *Amblema plicata* (Say 1817), the three-ridge naiad (Mollusca: Bivalvia). Ph.D. thesis, Ohio State University, Columbus. 174 pp.

Sterrett, S. S., and L. D. Saville. 1974. A technique to separate the annual layers of a naiad shell (Mollusca, Bivalvia, Unionacea) for analysis by neutron activation. Bull. Am. Malacol. Union Inc. 1974:55-57.

Strayer, D. 1980. The freshwater mussels (Bivalvia: Unionidae) of the Clinton River, Michigan, with comments on man's impact on the fauna, 1870-1978. Nautilus 94:142-149.

Taylor, R. W. 1980. A survey of the freshwater mussels of the Ohio River from Greenup Locks and Dam to Pittsburgh, Pennsylvania. U.S. Army Corps of Engineers, Huntington District, Huntington, W. Va. 71 pp.

Terhaar, C. J., W. S. Ewell, S. P. Dziuba, W. W. White, and P. J. Murphy. 1977. A laboratory model for evaluating the behavior of heavy metals in an aquatic environment. Water Res. 11:101-110.

Tessier, A., P. G. C. Campbell, J. C. Auclair, and M. Bisson. 1984. Relationships between the partitioning of trace metals in sediments and their accumulation in the tissues of the freshwater mollusc *Elliptio complanata* in a mining area. Can. J. Fish. Aquat. Sci. 41:1463-1472.

Thiel, P. A. 1981. A survey of unionid mussels in the Upper Mississippi River (Pools 3 through 11). Wis. Dep. Nat. Resour. Tech. Bull. 124. 24 pp.

U.S. Army Corps of Engineers. 1984. Chemical analyses of sediments and mussel tissue Pool 15, Upper Mississippi River. U.S. Army Corps of Engineers, Rock Island, Ill. 19 pp.

van der Schalie, H. 1938. Contributing factors in the depletion of naiades in eastern United States. Basteria 3:51-57.

van der Schalie, H., and A. van der Schalie. 1950. The mussels of the Mississippi River. Am. Midl. Nat. 44:448-466.

Varanka, I. 1977. The effect of some pesticides on the rhythmic activity of adductor muscle of fresh-water mussel larvae. Acta Biol. Acad. Sci. Hung. 28:317-332.

Varanka, I. 1978. Effect of some pesticides on the rhythmic adductor muscle activity of fresh-water mussel larvae. Acta Biol. Acad. Sci. Hung. 29:43-55.

Vinogradov, A. P. 1953. The elementary chemical composition of marine organisms. Memoir Sears Foundation for Marine Research, Yale University, New Haven, Conn. 647 pp.

Wiebe, A. H. 1927. Biological survey of the Upper Mississippi River, with special reference to pollution. Bull. U.S. Bur. Fish. 43:137-167.

Wiener, J. G., G. A. Jackson, T. W. May, and B. C. Cole. 1984. Longitudinal distribution of trace elements

(As, Cd, Cr, Hg, Pb, and Se) in fishes and sediments of the Upper Mississippi River. Pages 139–170 *in* J. G. Wiener, R. V. Anderson, and D. R. McConville, eds. Contaminants in the Upper Mississippi River. Butterworth Publishers, Boston, Mass.

Williams, J. C. 1969. Mussel fishery investigation Tennessee, Ohio and Green rivers final report. Ky. Dep. Fish Wildl. Resour. Proj. 4-19-R. 107 pp.

Wolfe, D. A., and C. L. Schelske. 1969. Accumulation of fallout radioisotopes by bivalve molluscs from the Lower Trent and Neuse rivers. Pages 493–504 *in* D. J. Nelson, F. C. Evans, S. I. Auerbach, P. B. Dunaway, F. F. Hooper, E. J. Kuenzler, T. R. Rice, C. A. Tryon, and R. G. Wiegert, eds. Proceedings of the second national symposium on radioecology. U.S. Atomic Energy Commission Conference 670503.

Yokely, P., Jr. 1972. Freshwater mussel ecology, Kentucky Lake, Tennessee, 1 May 1969–15 June 1972. Tennessee Game and Fish Commission, Nashville. Proj. 4-46-R. 133 pp.

Havlik, Marian E., and Leif L. Marking. 1987. **Effects of contaminants on naiad mollusks (Unionidae): a review.** U.S. Fish Wildl. Serv., Resour. Publ. 164. 20 pp.

Contaminants appear to have destroyed naiad mollusk populations directly by exerting toxic effects, or contributing to the elimination of essential food organisms or host fish. Various common contaminants have been reported to be toxic at the following concentrations (ppm): cadmium, 2; copper sulfate, 2 to 18.7; ammonia, 5; potassium, 11; chromium, 12.4; arsenic trioxide, 16; copper, 19; and zinc, 66. Naiad mollusks are important indicators of contaminants in the environment; residues in soft tissue indicate recent or current exposure, and residues in shells indicate past exposure.

Key words: Toxicity, naiad mollusks, tissue residues, chemical contamination, freshwater mussels, environmental stress.

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159. Research and Development Series: An Annotated Bibliography, 1889-1985, compiled by Thomas J. Cortese and Barbara A. Groshek. In press.
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